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Strong three-body decays of $\Lambda_c(2940)^+$ in a hadronic molecule picture

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The $\Lambda_c(2940)^+$ baryon with quantum numbers $J^P = \frac{1}{2}^+$ is considered as a hadronic molecule composed of a nucleon and D^* meson. We give predictions for the width of the strong three-body decay processes $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+\pi^+\pi^-$ and $\Lambda_c(2286)^+\pi^0\pi^0$ in this interpretation. Upcoming experimental facilities like a Super B factory at KEK or LHCb might be able to provide data on these decay modes.

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I. INTRODUCTION

The charmed baryon $\Lambda_c(2940)^+$ was originally observed by *BABAR* [1] and later on confirmed by the Belle Collaboration [2] as a resonant structure in the final state $\Sigma_c(2455)\pi \to \Lambda_c\pi\pi$. Both collaborations deduce values for mass and width with $m_{\Lambda_c} = 2939.8 \pm 1.3 \pm 1.0$ MeV, $\Gamma_{\Lambda_c} = 17.5 \pm 5.2 \pm 5.9$ MeV (*BABAR* [1]) and $m_{\Lambda_c} = 2938.0 \pm 1.3^{+2.0}_{-4.0}$ MeV, $\Gamma_{\Lambda_c} = 13^{+8}_{-5}{}^{+27}_{-7}$ MeV (Belle [2]) which are consistent with each other.

Theoretical interpretations of this new charmed baryon resonance were already discussed in the literature (see e.g. the short overview in Ref. [3]) including a conventional understanding in different types of three-quark and quark-diquark models [4]-[14]. In Ref. [11] it was proposed that the $\Lambda_c(2940)^+$ is a hadron molecule, where this state is regarded as a $D^{*0}p$ configuration with spin–parity being $J^P = \frac{1}{2}^-$ or $\frac{3}{2}^-$. This interpretation is due to the fact that the $\Lambda_c(2940)^+$ mass is just a few MeV below the $D^{*0}p$ threshold value and therefore strong coupling to this hadron channel is expected. It was also shown that the boson-exchange mechanism, involving the π, ω and ρ mesons, can provide binding for such $D^{*0}p$ con-

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figurations. But in a first variant of a unitary meson-baryon coupled channel model [12] the $\Lambda_c(2940)^+$ cannot be identified with a dynamically generated resonance. Hence a possible binding of $D^{*0}p$ remains to be examined.

We also studied the structure of the $\Lambda_c(2940)^+$ as a possible molecular state composed of a nucleon and a D^* meson within a formalism related to the compositeness condition [3, 15]. We analyzed its two-body strong and radiative partial decay widths for the channels of pD, $\Sigma_c(2455)\pi$ and $\Lambda_c(2286)\gamma$. In case of the two-body strong decays we tested two different spin-parity assignments for the $\Lambda_c(2940)^+$: $J^P = \frac{1}{2}^+$ and $\frac{1}{2}^-$. It was found that for $J^P = \frac{1}{2}^+$ the sum of the three partial widths is consistent with present observation, while for $\frac{1}{2}^-$ a severe overestimate for the total decay width is obtained. Hence we concluded in [15] that the choice of spin-parity $J^P = \frac{1}{2}^+$ is preferred in the molecular interpretation. Furthermore, the radiative decay $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+\gamma$ has also been estimated using the same approach [3] assigning the $J^P = \frac{1}{2}^+$ spin-parity to the $\Lambda_c(2940)^+$.

In this brief report we extend our previous analysis to estimate the two-pion decay channels of the $\Lambda_c(2940)^+$ as $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+\pi^+\pi^-$ or $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+\pi^0\pi^0$. Although these two-pion decay modes of the $\Lambda_c(2940)^+$ have also been discussed in Ref. [11] no quantitative results were presented yet. This is because an unknown coupling constant for the vertex $ND^*\Sigma_c$ occured in the considerations of Ref. [11]. However, a quantitative prediction for the three-body decay widths of $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + 2\pi$ could be done using information about two-body decays $\Lambda_c(2940)^+ \to \Sigma_c(2455) + \pi$ done in Ref. [15] and would be helpful for a measurement at the upcoming experimental facilities like Belle II at a Super B factory at KEK or with LHCb.

In this article the strong three-body decays of the $\Lambda_c(2940)^+$ baryon will be analyzed using the technique based on the compositeness condition [16, 17] for describing and treating composite hadron systems as developed in Refs. [15],[18]-[20]. In particular, in [15, 18, 19] recently observed unusual hadron states (like $D^*_{s0}(2317)$, $D_{s1}(2460)$, $X(3872)$, $Y(3940)$, $Y(4140)$, $Z(4430)$, $\Lambda_c(2940)$, $\Sigma_c(2800)$) were analyzed within the structure assumption as hadronic molecules. The compositeness condition implies that the renormalization constant of the hadron wave function is set equal to zero or that the hadron exists as a bound state of its constituents. It was originally applied to the study of the deuteron as a bound state of proton and neutron [16] (see also Ref. [20] for a further application of this approach to the case of the deuteron). Then it was extensively used in low–energy hadron phenomenology as the master equation for the treatment of mesons and baryons as bound states of light and heavy constituent quarks (see e.g. Refs. [17, 21]). By constructing a phenomenological Lagrangian including the couplings of the bound state to its constituents and the constituents to other final state particles we evaluated meson–loop diagrams which describe the different decay modes of the molecular states (see details in [18]).

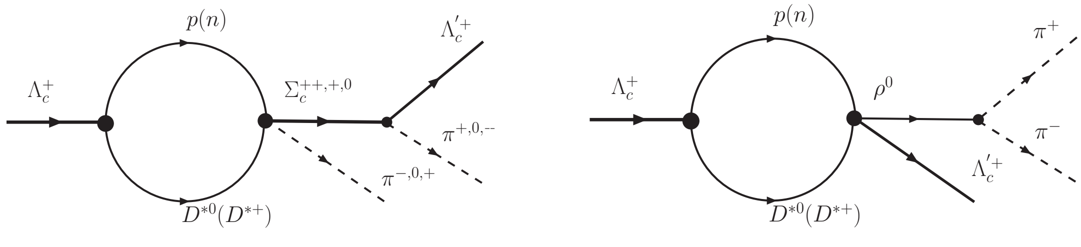
In the present paper we proceed as follows. In Sec. II we briefly review the basic ideas of our approach. Moreover, we consider the strong three-body decays of the $\Lambda_c(2940)^+$ baryon $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + 2\pi$ in this section. In the calculation of the three-body decay of the $\Lambda_c(2940)^+$ we consider two resonance contributions with the intermediate charmed baryon $\Sigma_c(2455)$ and ρ^0 meson. In Sec. III we present our numerical results, and, finally, in Sec. IV a short summary.

II. APPROACH

Here we briefly discuss the formalism for the study of the composite (molecular) structure of the $\Lambda_c(2940)^+$ baryon. In the following calculation we adopt spin and parity quantum numbers $J^P = \frac{1}{2}^+$ for the $\Lambda_c(2940)^+$, which is consistent with the observed strong decay width of the $\Lambda_c(2940)^+$ obtained in a hadronic molecule interpretation [15]. Following the original suggestion of Ref. [11] we consider this new baryon resonance as a superposition of molecular pD^{*0} and nD^{*+} components with the adjustable mixing angle θ:

$$|\Lambda_c(2940)^+\rangle = \cos\theta\; |pD^{*0}\rangle \;+\; \sin\theta\; |nD^{*+}\rangle\,. \tag{1}$$

The values $\sin\theta = 1/\sqrt{2}$, $\sin\theta = 0$ or $\sin\theta = 1$ correspond to the cases of ideal mixing, of a vanishing nD^{*+} or pD^{*0} component, respectively. Since the observed mass value of the $\Lambda_c(2940)^+$ with $m_{D^{*0}} +$



(a) (b)

FIG. 1: Diagrams contributing to the $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + 2\pi$ decay

$m_p - m_{\Lambda_c(2940)^+} = 5.94$ MeV and $m_{D^{*+}} + m_n - m_{\Lambda_c(2940)^+} = 10.54$ MeV lies closer to the pD^{*0} than to the nD^{*+} threshold, we might expect that the $|pD^{*0}\rangle$ configuration is the leading component. In this case the mixing angle θ should be relatively small and therefore we will vary its value from 0 to 25^0.

Our approach is based on an effective interaction Lagrangian describing the coupling of the $\Lambda_c(2940)^+$ to its constituents. We use a construction for the $\Lambda_c(2940)^+$ in analogy to mesons consisting of a heavy quark and a light anti-quark, i.e. the heavy D^* meson sets the center of mass of the $\Lambda_c(2940)^+$ while the light nucleon moves around the D^*. The distribution of the nucleon relative to the D^* meson is described by the correlation function $\Phi(y^2)$ depending on the Jacobi coordinate y. The simplest form of such a Lagrangian reads

$$\mathcal{L}_{\Lambda_c}(x) \;=\; \bar\Lambda_c^+(x)\,\gamma^\mu \int d^4y\,\Phi(y^2)\,\Big(g^0_{\Lambda_c}\,\cos\theta\,D^{*0}_\mu(x)\,p(x+y) + g^+_{\Lambda_c}\,\sin\theta\,D^{*+}_\mu(x)\,n(x+y)\Big) \;+\; \mathrm{H.c.}\,, \tag{2}$$

where $g^+_{\Lambda_c}$ and $g^0_{\Lambda_c}$ are the coupling constants of $\Lambda_c(2940)^+$ to the molecular nD^{*+} and pD^{*0} components. Here we explicitly include isospin breaking effects by taking into account the neutron-proton and the $D^{*+} - D^{*0}$ mass differences. Note that in our previous analysis [15] of strong two-body decays we restricted to the isospin symmetric limit. A basic requirement for the choice of an explicit form of the correlation function $\Phi(y^2)$ is that its Fourier transform vanishes sufficiently fast in the ultraviolet region of Euclidean space to render the Feynman diagrams ultraviolet finite. We adopt a Gaussian form for the correlation function. The Fourier transform of this vertex is given by

$$\tilde\Phi(p_E^2/\Lambda^2) \doteq \exp(-p_E^2/\Lambda^2)\,, \tag{3}$$

where p_E is the Euclidean Jacobi momentum. Here, Λ is a size parameter characterizing the distribution of the nucleon in the $\Lambda_c(2940)^+$ baryon, which also leads to a regularization of the ultraviolet divergences in the Feynman diagrams. From the analysis of the strong two-body decays of the $\Lambda_c(2940)^+$ baryon we found that $\Lambda \sim 1$ GeV [15]. The coupling constants $g^+_{\Lambda_c}$ and $g^0_{\Lambda_c}$ are determined by the compositeness condition [15–18, 21]. It implies that the renormalization constant of the hadron wave function is set equal to zero with:

$$Z_{\Lambda_c} = 1 - \Sigma'_{\Lambda_c}(m_{\Lambda_c}) = 0\,. \tag{4}$$

Here, $\Sigma'_{\Lambda_c}(m_{\Lambda_c})$ is the derivative of the $\Lambda_c(2940)^+$ mass operator (see details in [15]).

In the calculation of the three-body decay $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + 2\pi$ we consider two resonance contributions: with the intermediate charmed baryon $\Sigma_c(2455)$ [see Fig.1(a)] and for the ρ^0 meson [see Fig.1(b)] in the transition. Note, the diagram in Fig.1(b) only contributes to the process with a charged $\pi^+\pi^-$ pair in the final state. The full matrix element of the three-body decay $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + 2\pi$ is calculated using a phenomenological Lagrangian formulated in terms of hadronic degrees of freedom with:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\Lambda_c} + \mathcal{L}^a + \mathcal{L}^b\,. \tag{5}$$

The Lagrangian contains the following terms — the coupling of $\Lambda_c(2940)^+$ with the constituents ($\mathcal{L}_{\Lambda_c}$), the terms $\mathcal{L}^a$ and $\mathcal{L}^b$ describing the two-step transitions of the $\Lambda_c(2940)^+$ constituents to the final state

of Figs.1(a) and 1(b), respectively. In particular, the term

$$\mathcal{L}^a = \mathcal{L}_{\pi D^* N \Sigma_c} + \mathcal{L}_{\pi \Sigma_c \Lambda_c'} \tag{6}$$

contains the $\pi D^* N \Sigma_c$ and $\pi \Sigma_c \Lambda_c'$ couplings. These vertices are deduced from the SU(4) symmetric Lagrangians originally derived in [22] and then extensively employed in our formalism in Refs. [3, 15, 19]:

$$\begin{aligned}
\mathcal{L}_{\pi^- D^{*0} p \Sigma_c^{++}} &= \left[\frac{1}{4}(g_1+g_2) - \frac{3}{2}g_3\right] \bar{\Sigma}_c^{++} \pi^- i\gamma^\mu \gamma_5 p D_\mu^{*0} \ + \ \text{H.c.}\,, \\
\mathcal{L}_{\pi^- D^{*+} n \Sigma_c^{++}} &= -\frac{3}{2} g_3 \bar{\Sigma}_c^{++} \pi^- i\gamma^\mu \gamma_5 n D_\mu^{*+} \ + \ \text{H.c.}\,, \\
\mathcal{L}_{\pi^0 D^{*0} p \Sigma_c^{+}} &= \frac{1}{2}\left[\frac{1}{4}(g_1+g_2) - 3g_3\right] \bar{\Sigma}_c^{+} \pi^0 i\gamma^\mu \gamma_5 p D_\mu^{*0} \ + \ \text{H.c.}\,, \\
\mathcal{L}_{\pi^0 D^{*+} n \Sigma_c^{+}} &= \frac{1}{2}\left[\frac{1}{4}(g_1+g_2) - 3g_3\right] \bar{\Sigma}_c^{+} \pi^0 i\gamma^\mu \gamma_5 n D_\mu^{*+} \ + \ \text{H.c.}\,, \\
\mathcal{L}_{\pi^+ D^{*0} p \Sigma_c^{0}} &= -\frac{3}{2} g_3 \bar{\Sigma}_c^{0} \pi^+ i\gamma^\mu \gamma_5 p D_\mu^{*0} \ + \ \text{H.c.}\,, \\
\mathcal{L}_{\pi^+ D^{*+} n \Sigma_c^{0}} &= \left[\frac{1}{4}(g_1+g_2) - \frac{3}{2}g_3\right] \bar{\Sigma}_c^{0} \pi^+ i\gamma^\mu \gamma_5 n D_\mu^{*+} \ + \ \text{H.c.}\,,
\end{aligned} \tag{7}$$

and

$$\mathcal{L}_{\pi \Sigma_c \Lambda_c'^+} = -\frac{1}{2}\sqrt{\frac{3}{2}}(g_2' - \frac{1}{2}g_1')\bar{\Lambda}_c'^+ i\gamma^5 \pi \Sigma_c + \ \text{H.c.}\,. \tag{8}$$

The effective couplings g_i and g_i' are fixed as [3, 15, 19]

$$\begin{aligned}
&g_1 = 0, \quad g_2 = -\frac{2}{5F_\pi} g_A g_{\rho\pi\pi}, \quad g_3 = -\frac{2}{3F_\pi} g_A g_{\rho\pi\pi}\,, \\
&g_1' = 0, \quad\ \ g_2' = -\frac{4}{5}\sqrt{2} g_{\pi NN}\,.
\end{aligned} \tag{9}$$

Here $F_\pi = 92.4 MeV$ is the pion decay constant, $g_{\pi NN} = 13.2$ is the pion-nucleon coupling constant, $g_A = 1.2695$ is the nucleon axial charge, $g_{\rho\pi\pi} = 6$ is the coupling of the ρ meson to pions. We also introduce the notation $\Lambda_c^{'+}$ for the $\Lambda_c(2286)^+$ baryon.

The effective Lagrangian $\mathcal{L}^b$ involved in the calculation of the diagram Fig.1(b) also contains two terms:

$$\mathcal{L}^b = \mathcal{L}_{\rho D^* N \Lambda_c'} + \mathcal{L}_{\rho\pi\pi}\,. \tag{10}$$

Here, $\mathcal{L}_{\rho\pi\pi}$ is the effective Lagrangian of the $\rho\pi\pi$ coupling having the standard form

$$\mathcal{L}_{\rho\pi\pi} = g_{\rho\pi\pi} \rho_k^\mu \pi_i \partial_\mu \pi_j \epsilon_{ijk}, \tag{11}$$

where i, j, k represent the isospin indices. The Lagrangian $\mathcal{L}_{\rho D^* N \Lambda_c'}$ can be derived using the procedure suggested in Ref. [23]. In particular, we start with the non-minimal (tensorial) $ND^*\Lambda_c'$ coupling

$$\mathcal{L}_{D^* N \Lambda_c'} = -g_{D^* N \Lambda_c'}\, \kappa_{D^* N \Lambda_c'}\, \bar{N}\, \sigma^{\mu\nu}\, \partial_\nu\, D_\mu^* \Lambda_c' \ + \ \text{H.c.}\,, \tag{12}$$

where the couplings $g_{D^* N \Lambda_c'}$ and $\kappa_{D^* N \Lambda_c'}$ are fixed as [3, 23]:

$$g_{D^* N \Lambda_c'} = -\frac{\sqrt{3}}{2} g_{\rho\pi\pi}\,, \quad \kappa_{D^* N \Lambda_c'} = 2.65\,. \tag{13}$$

In a next step we gauge the derivative acting on the D^* meson by introducing the ρ^0-meson field as:

$$\partial_\nu D^*_\mu \to (\partial_\nu - \frac{i}{2} g_{\rho\pi\pi}\rho^0_\nu)\, D^*_\mu \,. \tag{14}$$

It finally results in the $\rho^0 D^* N \Lambda_c'$ coupling:

$$\mathcal{L}_{\rho D^* N\Lambda_c'} = \frac{g_{\rho D^* N\Lambda_c'}}{2M_N} \bar{N} D^{*+}_\mu \, i\sigma^{\mu\nu}\, \rho_\nu \, \Lambda_c^{'+} \; + \; \text{H.c.}\,, \tag{15}$$

where $g_{\rho D^* N\Lambda_c'} = g_{\rho\pi\pi} g_{D^* N\Lambda_c'} \kappa_{D^* N\Lambda_c'}/2$.

In the evaluation of the two diagrams of Fig. 1 we use the standard free propagators for the intermediate particles:

$$\begin{aligned} iS_N(x-y) &= \langle 0|TN(x)\bar{N}(y)|0\rangle = \int \frac{d^4k}{(2\pi)^4 i}\, e^{-ik(x-y)} S_N(k), \\ S_N(k) &= \frac{1}{m_N - \not{k} - i\epsilon} \end{aligned} \tag{16}$$

for the nucleons and

$$\begin{aligned} iS^{\mu\nu}_{D^*}(x-y) &= \langle 0|TD^{*\,\mu}(x) D^{*\,\nu\,\dagger}(y)|0\rangle = \int \frac{d^4k}{(2\pi)^4 i}\, e^{-ik(x-y)} S^{\mu\nu}_{D^*}(k)\,, \\ S^{\mu\nu}_{D^*}(k) &= \frac{-g^{\mu\nu} + k^\mu k^\nu/m^2_{D^*}}{m^2_{D^*} - k^2 - i\epsilon} \end{aligned} \tag{17}$$

for the D^* vector mesons. The contributions of the intermediate resonance states, the $\Sigma_c(2455)$ baryon and the ρ meson, are described by Breit–Wigner type propagators. The related expressions are given in momentum space by

$$S_{\Sigma_c}(k) = \frac{M_{\Sigma_c} + \not{k}}{M^2_{\Sigma_c} - k^2 - iM_{\Sigma_c}\Gamma_{\Sigma_c}} \tag{18}$$

for the Σ_c baryon, and

$$S_\rho(k) = \frac{1}{M^2_\rho - k^2 - iM_\rho\Gamma_\rho} \tag{19}$$

for the ρ-meson, where $\Gamma_{\Sigma_c} \simeq 2.2$ MeV and $\Gamma_\rho = 149.1$ MeV are the total widths of the Σ_c and ρ-meson, respectively.

The three-body decay width of $\Lambda_c(2940)^+$ is calculated according to the standard formula

$$\Gamma = \frac{\beta}{512\pi^3 M^3_{\Lambda_c}} \int\limits_{4M^2_\pi}^{(M_{\Lambda_c} - M_{\Lambda_c'})^2} ds_2 \int\limits_{s_1^-}^{s_1^+} ds_1 \sum_{\text{pol}} |M_{\text{inv}}|^2 \tag{20}$$

where β is the factor taking into account identical particles in the final state ($\beta = 1$ for the mode with a charged $\pi^+\pi^-$ pair and $\beta = 1/2$ for the mode containing two neutral pions). Here, M_{inv} is the invariant matrix element, the symbols $s_1^\pm$ represent

$$s_1^\pm = M^2_\pi + \frac{1}{2}\left(M^2_{\Lambda_c} + M^2_{\Lambda_c'} - s_2 \pm \lambda^{1/2}(s_2, M^2_{\Lambda_c}, M^2_{\Lambda_c'}) \sqrt{1 - \frac{4M^2_\pi}{s_2}} \right) \tag{21}$$

and

$$\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz \tag{22}$$

is the Källen function. We use the following set of the invariant Mandelstam variables (s_1, s_2, s_3):

$$\begin{aligned} s_1 &= (p-p_3)^2 = (p_1+p_2)^2\,, \\ s_2 &= (p-p_1)^2 = (p_2+p_3)^2\,, \\ s_3 &= (p-p_2)^2 = (p_1+p_3)^2\,, \\ s_1+s_2+s_3 &= M^2_{\Lambda_c} + M^2_{\Lambda_c'} + 2M^2_\pi\,, \end{aligned} \tag{23}$$

where p, p_1, p_2 and p_3 are the momenta of Λ_c, Λ_c' and pions, respectively.

III. NUMERICAL RESULTS

For our numerical calculations the hadron masses are taken from the compilation of the Particle Data Group [24]. The only free parameters in our calculation are the dimensional parameter Λ and the mixing angle θ. As mentioned before, in our approach the parameter Λ describes the distribution of the nucleon around the D^* which is located in the center-of-mass of the $\Lambda_c(2940)^+$. Here, as in previous calculations [3, 15], we consider a variation of Λ from 0.75 to 1.25 GeV. The parameter θ is varied in the interval $(0-20)^0$.

For the decay channel $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + \pi^0\pi^0$ the graph of Fig.1(b) does not contribute and only Fig.1(a) does with the intermediate Σ_c^+ resonance. In Table I we give the predictions for the three-body decay width $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + \pi^0\pi^0$, proceeding via the $\Sigma_c(2455)^+$, for three different cases of the regularization parameter Λ and for a variety of mixing angles θ in the interval $(0-25)^0$. In Table II we list the results for the mode $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + \pi^+\pi^-$ with an intermediate Σ_c [Fig.1(a)]. The two values in the parentheses reflect the contributions of Σ_c^{++} and Σ_c^0, respectively. The full results of Fig.1(a) and Fig.1(b) are given in Table III. Values in the parentheses represent the contribution of Fig.1(b) only.

From the results listed in Tables I-III we find that the processes with intermediate Σ_c baryons play the by far dominant role in the decay especially because of their very narrow widths. The diagram of Fig.1(b), with a ρ propagator, is completely negligible. In addition, our results are rather sensitive to a variation of the scale parameter Λ. This should be obvious since the ultraviolet divergence of the diagrams is regularized by this quantity. Smaller values of Λ lead to a reduction in the predictions for the decay widths. The results are also very sensitive to a variation of the mixing parameter θ. An increase of θ leads to a larger decay width. The decay amplitudes of the two molecular components pD^{*0} and nD^{*+} add up in constructive interference. The magnitude of the two respective transition amplitudes is however different. This effect can be traced to the difference in $g^0_{\Lambda_c}$ and $g^+_{\Lambda_c}$ because of slight isospin violation, to the coupling constants $g_{\pi D^* BB_h}$ in Eq. (7) for the two components and also to the different loop integrals.

IV. SUMMARY

To summarize, we have pursued a hadronic molecule interpretation of the recently observed charmed baryon $\Lambda_c(2940)^+$. We studied the consequences for the three-body decay of $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + 2\pi$ which could be observed in a forthcoming round of experiments. Here, the $\Lambda_c(2940)^+$ is regarded as a superposition of $|pD^{*0}\rangle$ and $|nD^{*+}\rangle$ components with the explicit admixture expressed by the variable mixing angle θ. Furthermore, we used the spin-parity assignment $J^P = \frac{1}{2}^+$ for the $\Lambda_c(2940)^+$ as based on a previous analysis of the observed decay modes. In our calculation we employed the extended SU(4) chiral Lagrangians to describe the interaction terms contained in $\mathcal{L}_{\pi D^* BB_h}$ and $\mathcal{L}_{\pi BB'}$. Therefore, the necessary couplings $g_{\pi D^* BB_h}$ and $g_{\pi BB'}$ are well determined. The numerical results for the decay widths of the transition processes $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + \pi^+\pi^-$ and $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + \pi^0\pi^0$ were given. We also indicated the explicit contributions resulting from the two-step processes $\Lambda_c(2940)^+ \to \Sigma_c^{++}\pi^- \to \Lambda_c(2286)^+ + \pi^+\pi^-$, $\Lambda_c(2940)^+ \to \Sigma_c^0\pi^+ \to \Lambda_c(2286)^+ + \pi^+\pi^-$, $\Lambda_c(2940)^+ \to \Sigma_c^+\pi^0 \to \Lambda_c(2286)^+ + \pi^0\pi^0$, and $\Lambda_c(2940)^+ \to \rho^0\Lambda_c(2286)^+ \to \Lambda_c(2286)^+ + \pi^+\pi^-$. It is shown that the interactions of the chiral

Lagrangian embedded in Fig. 1(a) are by far dominant while the contribution of Fig. 1(b) is essentially negligible. The results for the two-pion decay widths are of the order of several MeV. The charged decay mode involving $\pi^+\pi^-$ is less than two times larger than the neutral $\pi^0\pi^0$ mode. This deviation from a ratio of two is caused by isospin breaking effects in the masses and in the effective coupling constants. Our results for the three-body decay widths present another test for the molecular interpretation of the $\Lambda_c(2940)^+$, where these decays are hopefully accessible at new facilities like the Super B factory at KEK or at LHCb.

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Table I. Three-body decay widths for $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+\pi^0\pi^0$ (in MeV) for different values of the parameters θ and Λ.

θ	$\Lambda = 1.25$ GeV	$\Lambda = 1$ GeV	$\Lambda = 0.75$ GeV
0^0	3.755	2.693	1.646
5^0	3.994	2.863	1.750
10^0	4.234	3.034	1.855
15^0	4.474	3.204	1.960
20^0	4.714	3.375	2.065

Table II. Three-body decay widths for $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+\pi^+\pi^-$ (in MeV) with the diagram Fig.1(a) for different values of θ and Λ. The values in the parentheses represent the contributions from Σ_c^0 and Σ_c^{++}, respectively.

θ	$\Lambda = 1.25$ GeV	$\Lambda = 1$ GeV	$\Lambda = 0.75$ GeV
0^0	6.010(1.930,1.568)	4.311(1.384,1.125)	2.729(0.876,0.712)
5^0	6.392(2.040,1.679)	4.583(1.462,1.204)	2.899(0.925,0.762)
10^0	6.776(2.150,1.792)	4.855(1.541,1.284)	3.070(0.974,0.812)
15^0	7.160(2.259,1.905)	5.129(1.618,1.364)	3.241(1.023,0.862)
20^0	7.543(2.368,2.018)	5.401(1.696,1.445)	3.411(1.071,0.912)

Table III. Three-body decay widths $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+\pi^+\pi^-$ (in MeV) with diagrams of Figs.1(a) and 1(b) for different values of θ and Λ. Values in parentheses indicate the contributions of Fig.1(b) with an intermediate ρ meson.

θ	$\Lambda = 1.25$ GeV	$\Lambda = 1$ GeV	$\Lambda = 0.75$ GeV
0^0	$6.014(5.486 \times 10^{-3})$	$4.314(4.268 \times 10^{-3})$	$2.732(3.083 \times 10^{-3})$
5^0	$6.396(5.835 \times 10^{-3})$	$4.586(4.539 \times 10^{-3})$	$2.902(3.276 \times 10^{-3})$
10^0	$6.780(6.186 \times 10^{-3})$	$4.859(4.811 \times 10^{-3})$	$3.073(3.468 \times 10^{-3})$
15^0	$7.165(6.537 \times 10^{-3})$	$5.133(5.083 \times 10^{-3})$	$3.244(3.661 \times 10^{-3})$
20^0	$7.548(6.888 \times 10^{-3})$	$5.405(5.354 \times 10^{-3})$	$3.414(3.853 \times 10^{-3})$